TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 454

THE N.A.C.A. COMBUSTION CHAMBER GAS-SAMPLING VALVE AND SOME PRELIMINARY TEST RESULTS

By J. A. Spanogle and E. C. Buckley
Langley Memorial Aeronautical Laboratory

Washington
March, 1933

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 454

THE N.A.C.A. COMBUSTION CHAMBER GAS-SAMPLING VALVE AND SOME PRELIMINARY TEST RESULTS

By J. A. Spanogle and E. C. Buckley

SUMMARY

A gas-sampling valve of the inertia-operated type has been designed by the staff of the National Advisory Committee for Aeronautics for procuring samples of the gases in the combustion chamber of internal-combustion engines at identical points in successive cycles so that the analysis of the gas samples thus procured may aid in the study of the process of combustion.

The operation of the valve is as follows: A valve cam driven by a flexible shaft compresses a cam spring through a tappet arm and, upon release, the inertia of the system lifts the valve stem from its seat against a stronger valve spring which then returns the valve stem to its seat. The valve as tested with apparatus for precise measurements had an opening period of 0.0004 second at all operating speeds and had a variation in time of opening of 0.00005 second at 750 cycles per minute. The movement of the top of the valve stem was 0.004 inch.

This gas-sampling valve has been used to investigate the CO_2 content of gases taken from the quiescent combustion chamber of a high-speed compression-ignition engine when operating with two different multiple-orifice fuel-injection nozzles. An analysis of the gas samples thus obtained shows that the state of quiescence in the combustion chamber is maintained during the combustion of the fuel.

INTRODUCTION

Attempts to follow the course of combustion in the cylinder of the internal-combustion engine have been directed along three general lines. One method is to calculate the amounts of fuel required to be burned to maintain the pressures shown on an indicator card. A second method is to follow the progress of the flame travel by any one of several optical or electrical devices. The third method is to follow the course of combustion by chemical analysis of samples of gas removed from the combustion chamber during a small time interval of identical phasing during successive cycles. A series of such samples taken at different stages in the process of combustion makes it possible to follow the chemical changes that take place inside the engine cylinder.

The field of application of gas sampling has been extended by the increasing use of valve overlap for scavenging the combustion chambers of four-stroke cycle fuel injection engines because, when operating with this type of scavenging, the conventional composite sample of gas taken from the exhaust pipe would contain varying amounts of air that had not been involved in the combustion process. Therefore, the analyses of samples of exhaust gases from a scavenged engine lose their significance and true samples of the gases involved in the combustion process may be obtained only from the engine cylinder.

The instrument used to procure such samples is commonly known as a "sampling valve." This device is a small stroboscopic valve that opens for a short period at corresponding points in successive cycles to allow the removal of a small portion of the cylinder contents adjacent to the valve opening. Several sampling valves have been designed by different investigators, that of Withrow, Lovell, and Boyd, of General Motors (reference 1) being one of the best known. A study of the available literature (references 1 to 6) indicated that ~~in~~ the design of a gas-sampling valve, the requirements most difficult to fulfill are that the valve have a short open period and also consistent phasing.

For purposes of design, 4° crank angle (or 0.0004 second at 1,500 r.p.m.) was used as the desirable value of the open period. The allowable variation of this period or of the phasing was limited to 0.0001 second. In order to keep this variation in phasing at a minimum, there should be as small a time interval as possible between the action that instigates the opening and the actual opening of the valve, because, if this interval were large, relatively small variations in it would cause unpermissible variations in phasing. The value decided upon for the stem lift was 0.006 inch. It was required that both the duration of opening and the stem lift be adjustable, since there was no way of knowing if the lift and period values given above would be satisfactory. A required frequency of opening of 1,000 times per minute was specified. Inasmuch as the valve was intended for use in several cylinder heads in various positions, it would have to be extremely adaptable and the method of driving would have to allow these changes in location without excessive alteration of the drive.

This latter requirement of adaptability made electrical operation seem desirable but it was found that operation with reasonable values of current would require too long a period between the action of the circuit breaker and the action of the valve with either direct or inertia operation. Hydraulic operation was considered possible, but trouble was anticipated from reflected pressure waves. Direct mechanical operation was discarded because of obvious difficulties in obtaining a short adjustable period of opening and consistent action throughout the speed range.

The inertia method of mechanical operation appeared to most nearly fulfill the requirements imposed but instead of using an inertia force that varied with speed (reference 1) and therefore varied the duration of opening, it was decided to use an inertia force that remained constant for a particular adjustment and consequently gave the same time duration of opening regardless of speed.

The use of the sampling valve in conjunction with a pressure gage as a pressure indicator was given some consideration during the design of the apparatus and, although the main purpose of the valve was the procurement of gas samples, it was made sufficiently strong and tight to withstand combustion pressures.

The staff of the N.A.C.A. had completed the design and had started the construction of the valve during 1931, but it was not used for any investigation of combustion until 1932.

DESCRIPTION OF VALVE

As a result of the preliminary investigation, an inertia or hammer-operated mechanically driven valve was constructed. In this valve a definite amount of energy is utilized to set a mass in motion. When this mass strikes a projection on the valve stem, the kinetic energy of the mass is utilized in lifting the valve stem against the action of a spring.

The method of operation may be seen from Figure 1. A cam and a tappet arm compress a spring, storing therein potential energy. This spring, upon release by the cam, converts its potential energy into kinetic energy of the tappet arm, spring retainer, and other parts. This group strikes a nut on the valve stem, knocking the valve stem off its seat. This movement is opposed by a stiff valve spring which absorbs the energy in a very short travel and then quickly returns the valve stem to its seat.

Figure 2 shows two views of the assembled valve without its driveshaft or piping connected. Figure 3 shows the parts of the disassembled valve. The following description of some of these parts will serve to explain more fully their construction and operation.

Valve stem.- A needle type of valve was chosen in preference to a poppet valve, as experiments have shown some slight tendency for gas to start flowing through the needle type more quickly, because the movement of the needle valve assists the gas to overcome its inertia and starts the gas moving in the right direction for gas sampling.

Valve spring.- From space considerations an extremely concentrated spring was desired with a high force and very small deflection. These general characteristics were obtained by using a spring composed of "Belleville disks," which are dished spring-steel washers. Provision was made for changing the force on this spring by a nut which can be locked in position. The force/weight ratio of the spring and attendant parts indicates a theoretical acceleration of the valve stem of about 1200 g.

Cam spring.- The cam spring was required to have a greater range of adjustment, consequently of deflection, than the valve spring in order that the amount of potential energy stored in it could be varied for different operating conditions. Therefore, a helical spring formed of comparatively large diameter wire was used in order that the desired speed of operation could be attained. The force/weight ratio indicates a theoretical acceleration of the tappet arm when released by the cam of about 600 g.

Cam.- An involute cam, giving approximately equal lifts for equal time increments, was designed to minimize the shocks on the driving mechanism by allowing the load to be applied gradually. Provision was made for varying the movement of the follower by changing the clearance between it and the cam by the insertion of shims under the follower.

Both the cam and the follower were made reversible to anticipate necessary changes in the direction of rotation of the drive.

Diaphragm.- A diaphragm was incorporated in the valve to provide the gas seal instead of either the usual lapped fit or packing gland, thereby eliminating trouble due to friction in this fit caused either by the variations in temperature or by deposited carbon. It also provides a positive gas seal so that samples may be obtained with evacuated pipettes in addition to the use of mercury displacement. Pressure may be built up inside the valve during its use as a pressure indicator.

Cooling.- As it was desirable to stop combustion immediately after the gas passed the valve seat, a cooling jacket was provided as close to the seat as possible. Intimacy of contact between the gas and the cooled walls of the valve was obtained by causing the gas to pass in a thin layer through a narrow annular passage. In addition, the internal volume was kept at a minimum to increase the velocity of flow through the valve and to decrease the dead-space. This volume, including the air fitting, was found by displacement to be approximately 1.1 cm^3.

Method of driving.- A flexible shaft about 6 feet long was used to connect the valve to the engine. The shaft was of relatively large diameter for the power transmitted so that the variations in deflection might be kept as small as possible. In order to decrease the torque that it must transmit, the shaft was geared to run at its rated maximum speed of 4,000 r.p.m. and on the valve a 4:1 gear reduction was used. Incorporated in the gearing at the engine end was an epicyclic-gear arrangement to allow change of phasing of the valve. An eccentric to depress the rocker arm so that the follower was clear of the cam was incorporated as a means of stopping the action of the valve without stopping the drive.

Timing contact.- An insulated timing contact was mounted over the top of the valve stem to close an electrical circuit at the instant the stem reached its maximum lift. This contact was used in conjunction with a Strobo-rama and a scale on the engine flywheel to determine the phase point of the valve opening. The contact was completely insulated from the valve to allow its use with no danger of grounding either side of the circuit to the engine.

DETERMINATION OF CHARACTERISTICS

The valve was subjected to a series of tests to check its operation and secure information concerning its characteristics. These tests were made in part while the valve was operated in connection with apparatus for precise measurements of lift and duration of opening as shown in Figure 4. The other part of the testing was done with the valve mounted for normal operation on a single-cylinder compression-ignition test engine as shown in Figure 5.

Duration of opening.- Using the set-up shown in Figure 4, an electric motor was used to drive the sampling valve, Farnboro indicator recording unit, and contactor mechanism for a Stroborama. A contact was attached to the bottom of the valve so that it just touched the valve stem when it was seated. This contact was in series with the contactor mechanism operating the Stroborama. The closing of the circuit by the contactor would cause the Stroborama to flash unless the circuit was open at the valve owing to the stem being off its seat. In this case the flash would occur when it reseated. It is evident that no flash could occur at any phase angle at which the stem was lifted. This interval, during which the stem was lifted, was determined by observation of the scale on the rotating Farnboro drum as illuminated by these flashes.

As an approximate check, oil under 100 pounds per square inch pressure was fed through the outlet fitting and allowed to spray from the valve while running at normal speed. The duration of this spray was determined with the Stroborama. This method of checking the operation of the valve, although less precise than the other, is used as a routine check on account of its greater convenience.

With a particular adjustment the period as found by the first method was 0.0004 second and as determined by the second method was slightly over half that value. Owing to its inertia, the oil is late in starting from the valve, resulting in an effective period of less than the true period. There is no simple method of obtaining the effective period for a gas but it should much more closely approximate the actual period than it does with oil, owing to the lower inertia of the gas and the assistance given by the valve stem in starting flow into the valve.

Lift.- The use of a micrometer screw at the top of the valve stem to close a circuit through a neon lamp allowed the value of the lift to be found. The movement of the top of the stem was found to be 0.004 inch with the particular adjustment used.

Phasing.- It is important that an indication be given of the exact point at which the valve opens. For accurate work this phase relation must not vary. As mentioned previously, the determination of the phasing of the valve is accomplished through the operation of a Stroborama by a contact at the top of the valve. A marked flywheel is illuminated by the flash. Much more satisfactory indication of the point of opening was obtained by the use of the Stroborama than by relying on the closing of a simple circuit through a neon tube. In the Stroborama the slightest contact operates a tripping circuit which causes a bright flash of a neon lamp, allowing a very positive determination of the position of the flywheel at the instant of contact. Since this contact is made at the extreme of the movement of the top of the stem, it seemed advisable to correlate it with the movement at the valve seat. Again the set-up shown in Figure 4 was used. The contact at the bottom of the stem, using the method of the Farnboro indicator, recorded by a spark to the drum the point at which the stem left its seat. The point of maximum movement of the top of the stem was found by observing the scale on the Farnboro drum by the flashes of the Stroborama operated by the contact at the top of the stem. As a final check, oil was sprayed from the valve, as mentioned previously, and the start determined with the Stroborama.

Very close agreement between the three methods was observed with the anticipated exception that the start of the oil spray was approximately 0.0001 second later. The phasing was found to be very constant, the variation in time of opening being 0.00005 second at 750 cycles per minute. This constancy of phasing was maintained even with the flexible shaft drive, provided that sufficient care was observed in its operation. During the preceding work to determine the duration and phasing, no irregularities of seating were observed and it is believed that the stem seats accurately with no observable bounce.

Use of flexible shaft.- In lightly loaded shafts which have considerable curvature, as in this case, the torsional deflection between the ends owing to the friction of the casing is several times the deflection caused by the load.

This deflection varies greatly as the shaft is shifted slightly in position. Phase irregularities from this cause as great as 10° to 15° have been observed. After the position of the shaft had been determined for any installation, it was necessary to wire it in position so that no oscillation or weaving was possible. Likewise, the lubrication of the shaft was found to be very important and for this reason the casing was kept thoroughly packed with petrolatum. It was also observed that the phasing changed during the first few minutes of running because of increasing deflection of the shaft. The instrument was always run for a sufficient time, therefore, for this deflection to become constant before observations were started.

Frequency of operation.- The maximum speed at which the apparatus may be operated is dependent upon the maximum permissible speed of the flexible shaft which limits the operation to 1,000 cycles per minute. The maximum speed of the valve itself is above this value.

Limiting values of lift and duration.- There are several ways of changing the period and stem lift of the valve. Although variation of one affects the other, there is sufficient independence so that for any particular value of the period a range of values for the lift may be obtained.

The period may be varied from no opening to an opening of 0.001 second. Inertia of the gas would prevent any flow if the period were too short. Accuracy would be sacrificed if the period were too long. The value used is the shortest period in which a 200 cm³ sample may be obtained in the satisfactory time of approximately one minute. The lift and period are constant regardless of engine speed, the period being a constant length of time and not a constant number of engine degrees.

Pumping action.- The action of the valve was found to assist the flow of gas. With the valve operating in a chamber open to the atmosphere, a pressure was built up on a manometer connected to the gas outlet. The pressure varied with the period used and was observed between 1 inch and 2 inches of mercury. This pumping action assists in procuring the sample, particularly at low pressures. It is believed that a pumping characteristic of this nature is inherent in extremely short-period conical seat valves.

Very consistent results have been obtained in preliminary work with the valve as an indicator but a study of the magnitude and other characteristics of the correction due to pumping is necessary before the valve may be used for indicating true pressures in the combustion chamber.

ENGINE TESTS

The first engine tests of the gas-sampling valve were made for the purpose of testing the device for satisfactory operation when exposed to the heat of the engine and to test the efficacy of the cooling jacket.

The operation of the valve was entirely satisfactory during this and all subsequent tests to date. The valve was phased to open during combustion as shown by the pressure rise on an indicator card. The first samples were taken with CO_2 as a cooling medium and the cooling was sufficient to cause frost to form on the valve to within one-eighth inch of the cylinder head. The second set of samples was taken with a sufficient flow of water through the cooling jacket to maintain the external temperature of the valve somewhat below room temperature. As an analysis which was then made of the two sets of samples showed the same percentage of CO_2 in both of them, it was concluded that water cooling was as effective as the more expensive CO_2 cooling. All subsequent tests have been made with water cooling.

In the course of taking a series of samples, it has been made part of the routine to go back to a previous phase point and take at least one check sample in each series of six samples. In every case the analysis of the two samples has shown a satisfactory agreement.

Tests were made to determine whether or not the contents of the quiescent combustion chamber (reference 7) maintained their quiescent condition during combustion. Two series of ten samples each were taken with the valve located in the middle hole of N.A.C.A. No. 4 cylinder head. The first series was taken while using the standard 6-orifice fuel-injection nozzle and the second while using a nozzle with only two orifices, all other engine conditions being the same. Figure 6 indicates the arrangement of the sprays from the two nozzles and shows the results of the chemical analysis of the samples.

In the first series the increase of CO_2 is shown to be almost coincident with the rise of pressure in the cylinder. The analysis of the second series of samples showed absolutely no CO_2 although the indicator cards showed a rise in pressure quite similar to that obtained in the first series.

It has been suggested that the low final percentage of CO_2 may be due to the gas-sampling valve removing such a minute quantity that samples are obtained of only the inert exterior layer. This suggestion does not seem reasonable for, if a stagnant layer of gas of any appreciable thickness adhered to the combustion-chamber walls, it would eventually contain residual CO_2 which would be detected in the samples throughout the entire cycle. The authors prefer to attribute the low final percentage of CO_2 to the fact that the fuel injected was less than full-load fuel quantity and that the sampling valve was located in a region supplied with insufficient fuel to produce a greater quantity of CO_2 than was shown by the analyses.

The results of these tests indicate that the quiescent combustion chamber maintains its state of quiescence effectively even during the combustion of the fuel. Therefore, with this type of combustion chamber the amount of fuel that can be completely burned will depend upon the design of the fuel-injection nozzle and the thoroughness with which it distributes the fuel to the air in the different parts of the combustion chamber.

To date the valve has had over 50 hours of use. No trouble or excessive wear of any sort has developed other than occasional cracks in the diaphragm.

These preliminary tests have shown that the N.A.C.A. gas-sampling valve will give consistent and satisfactory service in removing composite samples of gas from a point in the combustion chamber of an internal combustion engine at a particular phase point of the engine cycle. The analysis of samples obtained in this way may lead to a better understanding of the process of combustion in a compression-ignition engine.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 14, 1933.

REFERENCES

1. Withrow, Lloyd, Lovell, W. G., and Boyd, T. A.: Following Combustion in the Gasoline Engine by Chemical Means. Ind. and Eng. Chem., Vol. 22, No. 9, Sept., 1930, pp. 945-951.

2. Lovell, Wheeler G., Coleman, John D., and Boyd, T. A.: Studies of Combustion in the Gasoline Engine. Ind. and Eng. Chem., Vol. 19, No. 3, March, 1927, pp. 373-378.

3. Alexander, D. H.: Airless Injection and Combustion of Fuel in the High Compression Heavy Oil Engine, Trans. Inst. of Marine Engineers, Vol. 39, Session 1927-1928, pp. 366-414.

4. De Juhasz. K. J.: The de Juhasz Indicator. Automobile Engineer, August, 1929, pp. 303-307.

5. Klusener, Otto: The Functioning of High Speed Two Stroke Cycle Carburetor Engines. Z.V.D.I., Vol. 74, No. 33, August 16, 1930, pp. 1154-1156.

6. Prescott, Ford L.: Indicators as a Means of Improving Aircraft-Engine Performance. S.A.E. Journal, Sept., 1932, pp. 361-370.

7. Spanogle, J. A., and Foster, H. H.: Basic Requirements of Fuel-Injection Nozzles for Quiescent Combustion Chambers. T.N. No. 382, N.A.C.A., 1931.

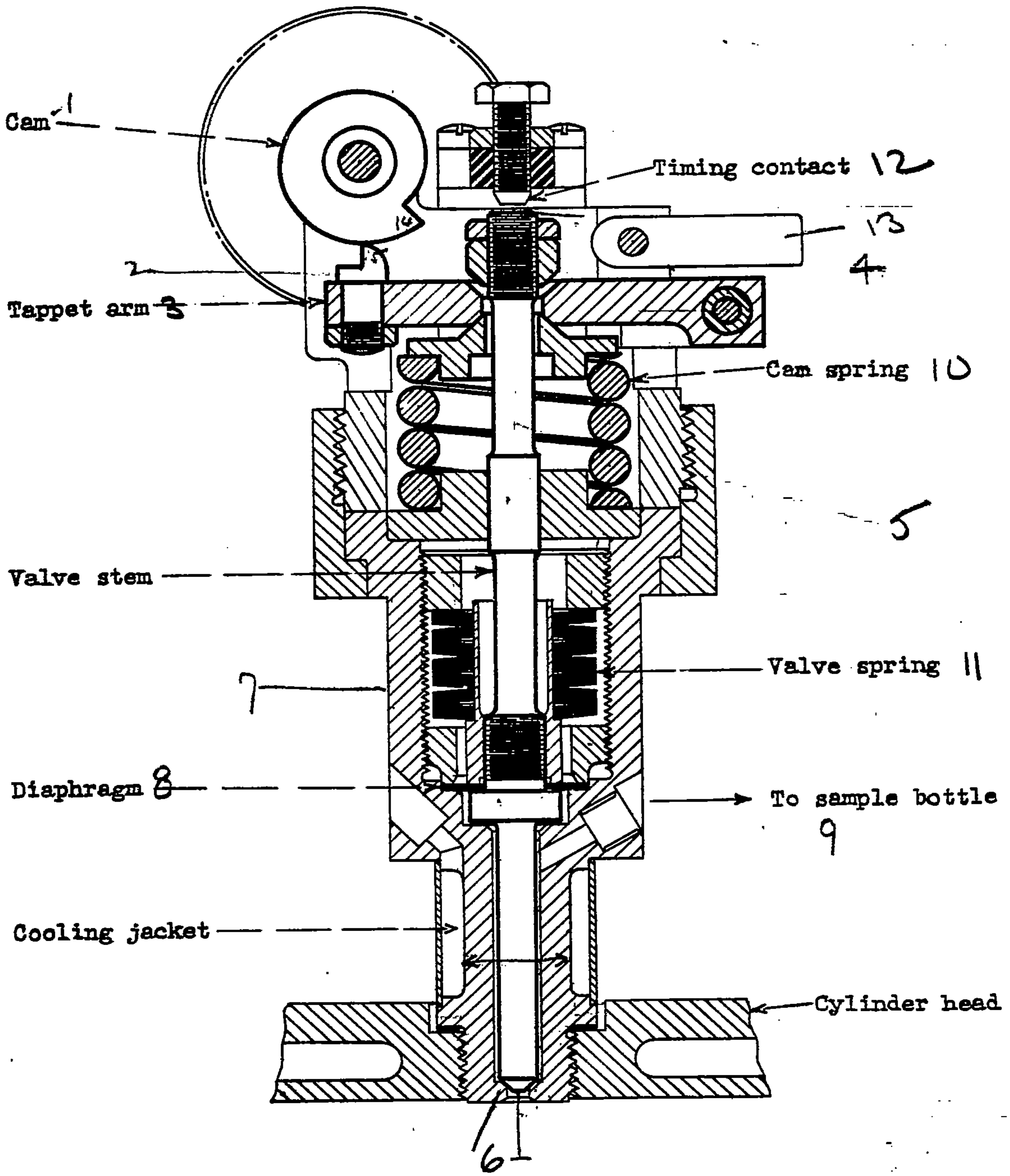

Figure 1.-Schematic diagram of N.A.C.A. gas-sampling valve.

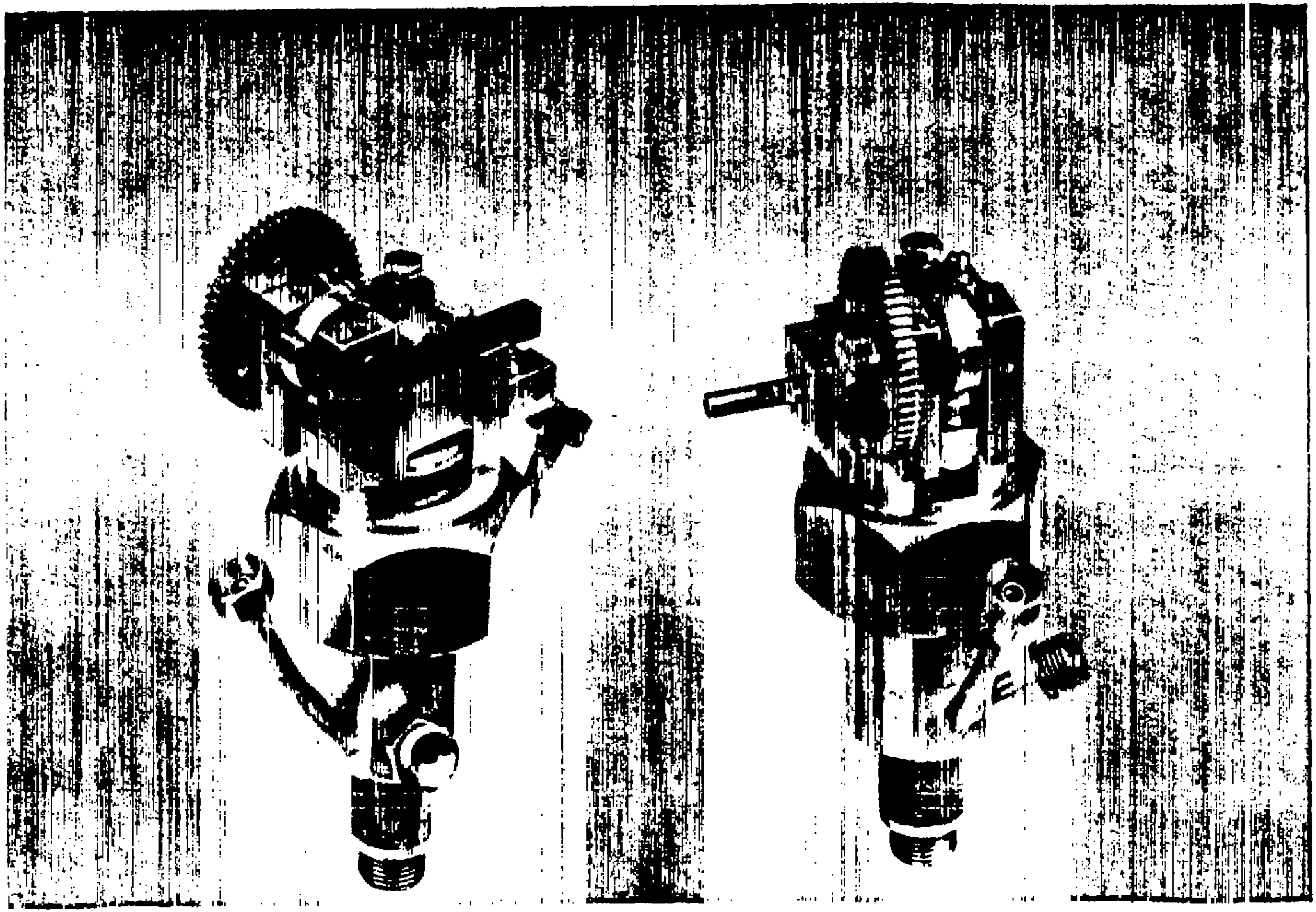

Figure 2.-N.A.C.A. gas-sampling valve (assembled).

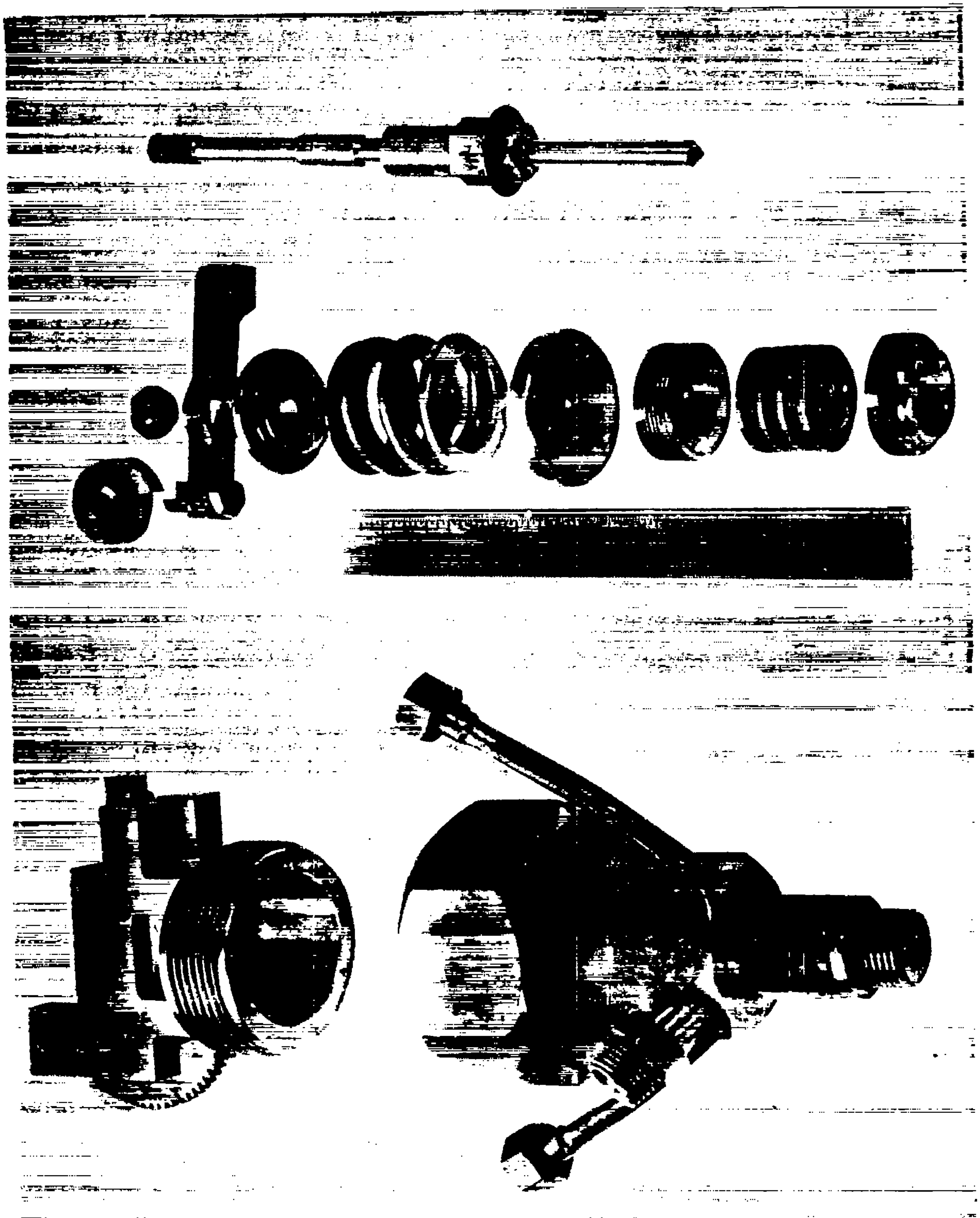

Figure 3.-N.A.C.A. gas-sampling valve (disassembled).

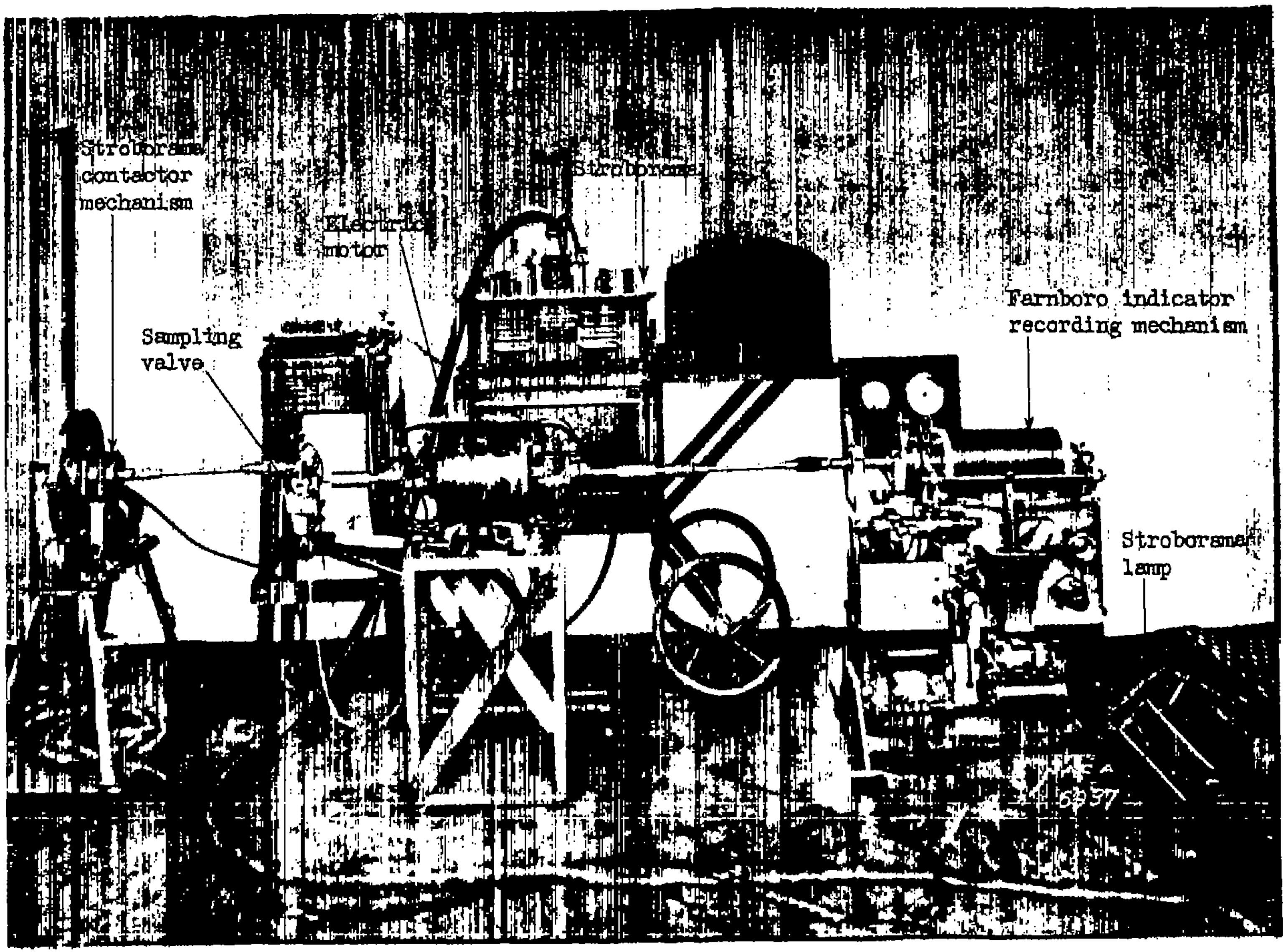

Figure 4.-Test apparatus

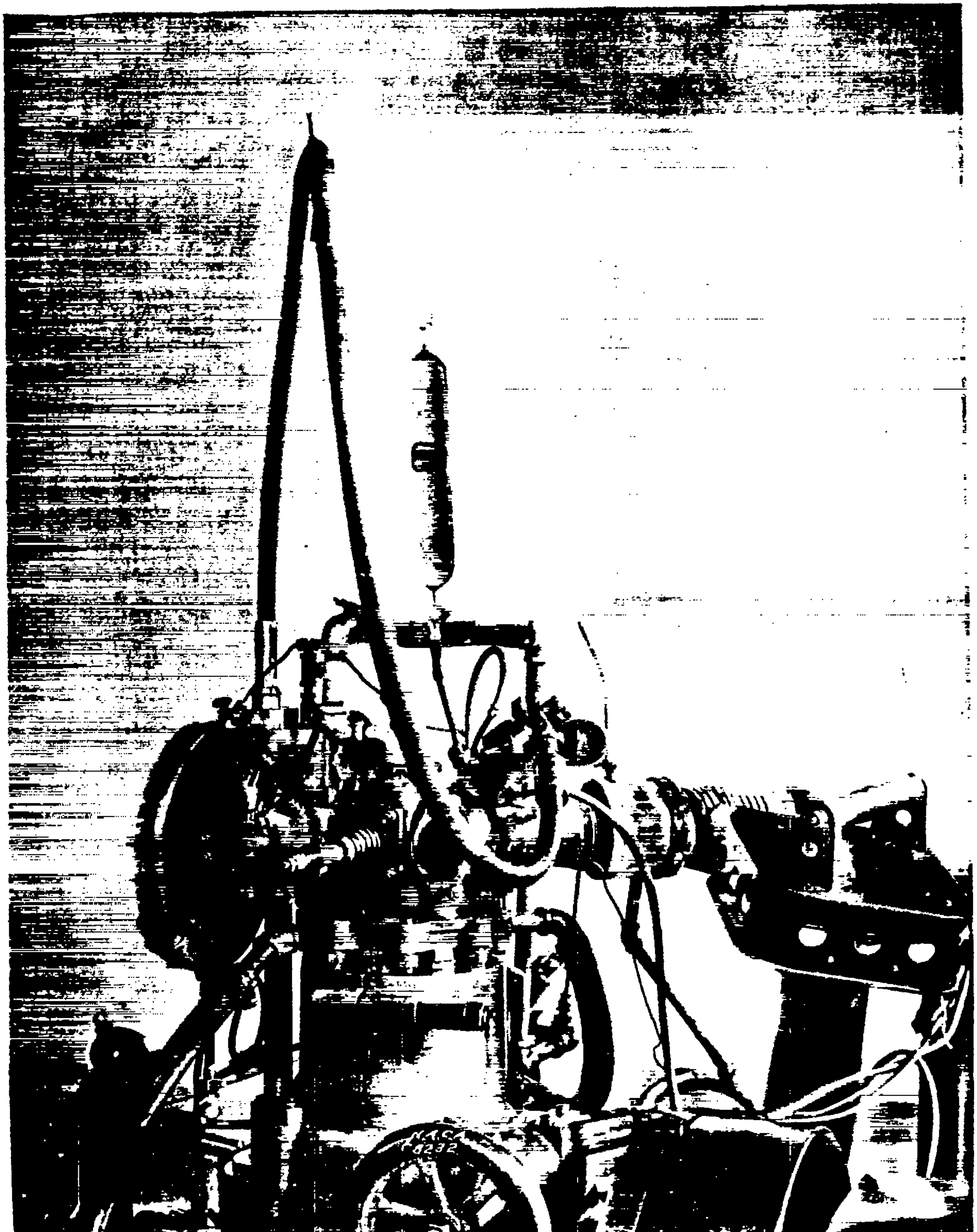

Figure 5.-Engine installation of N.A.C.A. gas-sampling valve.

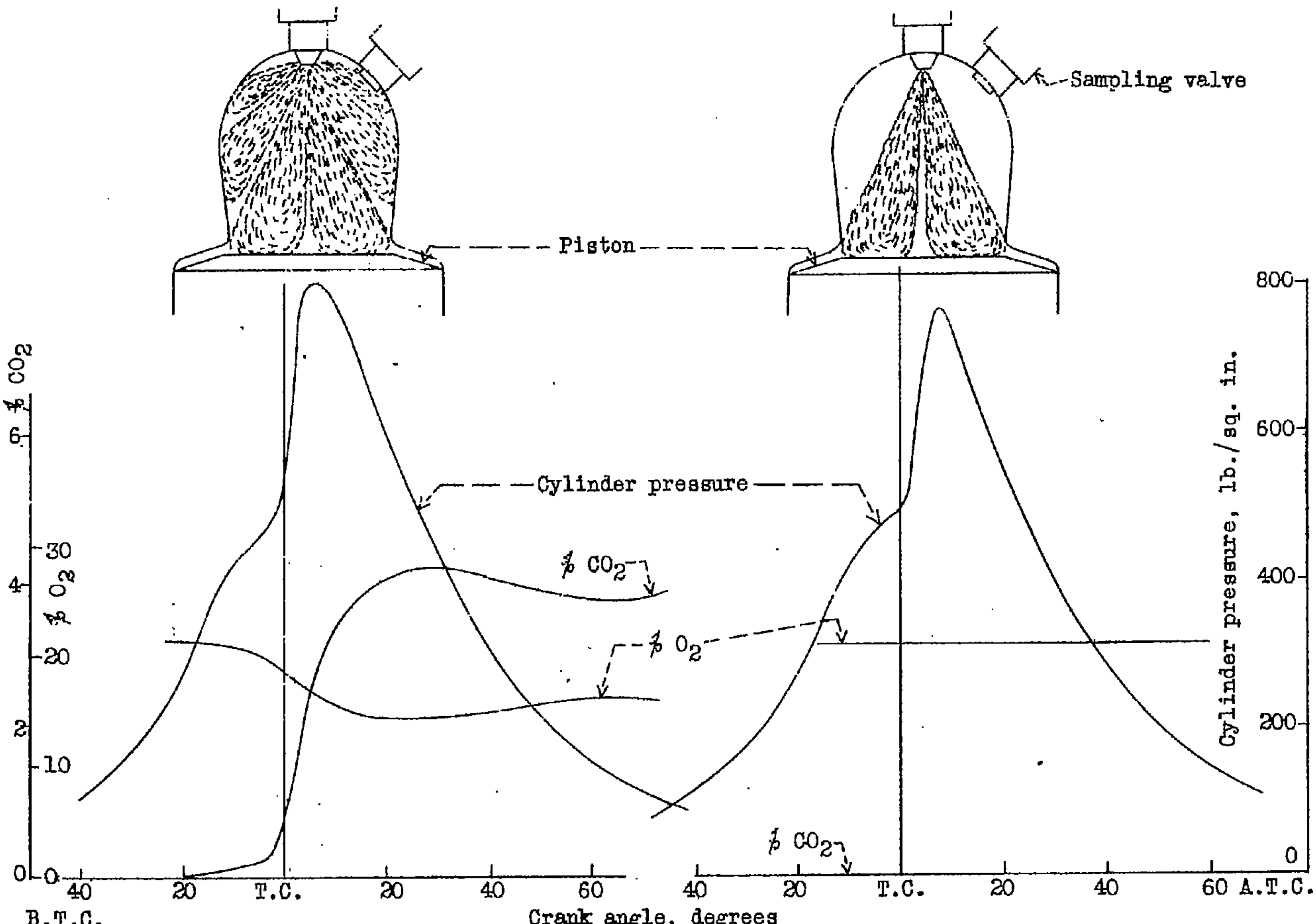

Figure 6.-Combustion process indicated by cylinder gas analysis.